

The Ejection of Low Mass Clumps During Star Formation

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Abstract. Modeling of the self-consistent formation and evolution of disks as a result of prestellar core collapse reveals an intense early phase of recurrent gravitational instability and clump formation. These clumps generally migrate inward due to gravitational interaction with trailing spiral arms, and can be absorbed into the central object. However, in situations of multiple clump formation, gravitational scattering of clumps can result in the ejection of a low mass clump. These clumps can then give rise to free-floating low mass stars, brown dwarfs, or even giant planets. Detailed modeling of this process in the context of present-day star formation reveals that these clumps start out essentially as Larson first cores and grow subsequently by accretion. In the context of Pop III star formation, preliminary indications are that the disk clumps may also be of low mass. This mechanism of clump formation and possible ejection provides a channel for the formation of low mass objects in the first generation of stars.

Keywords: stars: formation, accretion disks, hydrodynamics

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INTRODUCTION

Numerical simulations that can track the evolution all the way from prestellar core collapse through the self-consistent formation of a disk and its subsequent long-term evolution are revealing new insights into star, brown dwarf, and planet formation. Our group has published a series of papers [e.g., 1, 2, 3] that illustrate an early phase of disk evolution that is characterized by recurrent gravitational instability, and accretion driven by gravitational torques. Gravitational instability is triggered when accretion onto the disk drives the Toomre parameter of the disk below the critical value, resulting in the formation of gas clumps within nonlinear spiral arms. These clumps are generally driven inward through gravitational torques resulting from their interaction with trailing spiral arms. Some clumps are also dispersed due to tidal effects. Clumps that plunge inward to the central object can be invoked to explain the (FU Ori) luminosity bursts that are associated with young stellar objects [4]. Recent modeling [3] shows that the collapse of cores with sufficient mass and/or angular momentum can lead to disks with multiple clump formation in which the gravitational scattering of clumps leads to the ejection of low mass clumps. These clumps generally straddle the substellar limit, and may be the precursors of free-floating low mass stars, brown dwarfs, or even giant planets.

The above modeling is done in the thin-disk approximation, with a central sink cell of about 6 AU in radius, and a logarithmically spaced radial grid. These simplifications allow the modeling of the long-term evolution (> 1 Myr) of the disk and core

envelope structure. The combination of these features is generally not both feasible in fully three-dimensional simulations, even with adaptive mesh refinement. However, new three-dimensional simulations that resolve a large dynamic range of length scales have recently also found some of the same features, e.g., gravitational instability and episodic accretion [5].

MODEL & RESULTS

Figure 1 shows a sequence of column density images for a reference model presented in Basu & Vorobyov [3], at various times after the formation of a central object, on the full computational domain of 20,000 AU on each side. Fragments are formed as early as 0.05 Myr, but here we focus in on a narrow time window within which an ejection event occurs. Although clumps are generally torqued inward or sometimes disperse, under favorable conditions a clump within a multi-clump environment may be ejected through many-body interaction. The ejection is also aided by the nonaxisymmetric potential of the disk. The arrows point to a clump that undergoes an ejection. The speed of the ejected clump at the moment that it leaves the computational domain is about 0.9 km s^{-1} , which is a factor of three greater than the escape speed from the system. However, it is comparable to typical random speeds of young stellar objects within their host clusters. The total mass of the clump, calculated as the mass passing the computational boundary during the ejection event, is $0.15 M_{\odot}$. We speculate that upon contraction this clump may form a substellar object, given that a significant fraction of mass remains in the disk until it is ejected due to outflows and/or dispersed due to photoevaporation. Other models presented by Basu & Vorobyov [3] show the ejection of even substellar mass objects.

DISCUSSION AND CONCLUSIONS

The model presented here has important implications for the formation of free-floating low mass stellar or substellar objects in the Galaxy. But what are the implications for the first generation of stars?

The clumps in the models with solar metallicity start out as essentially Larson first cores, defined as objects of a Jeans mass at the density where optical depth unity is first reached. This means that their initial mass is about $0.01 M_{\odot}$ and they can grow subsequently by accretion from the disk, usually achieving a mass of about ten times this value, or $\sim 0.1 M_{\odot}$. Figure 2 shows the temperature-density relations for both $Z = Z_{\odot}$ and $Z = 0$ based on calculations of Omukai et al. [6]. While optical depth unity is reached at a number density of $n \simeq 10^{11} \text{ cm}^{-3}$ for solar metallicity, it is reached at $n \simeq 10^{16} \text{ cm}^{-3}$ for the $Z = 0$ case [6]. This is also the location of a local steepening of the temperature-density relation. The Jeans mass at this density and corresponding temperature $\simeq 2000 \text{ K}$ is $\sim \text{few} \times 0.01 M_{\odot}$. Preliminary calculations [7, 8] do find the formation of disk fragments of mass $\sim 1 M_{\odot}$, which is roughly consistent with the present-day simulations where the clumps grow to about ten times the initial Jeans mass. The formation, growth, and possible ejection of low mass Pop III stars through disk

fragmentation is thus a tantalizing possibility that can be clarified by future calculations.

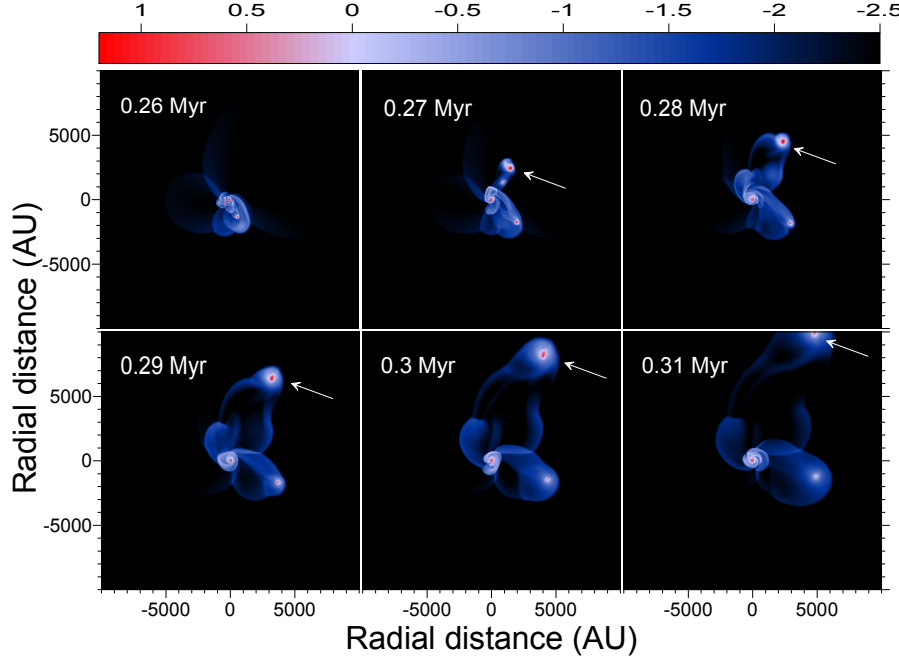


FIGURE 1. Gas surface density distribution (g cm^{-2} , log units) in a reference model at several time instances after the formation of a central star. The box size is 20,000 AU on each side and represents nearly the full extent of the computational domain. Arrows identify a clump that is ejected from the system after a multi-body interaction within the centrifugal disk.

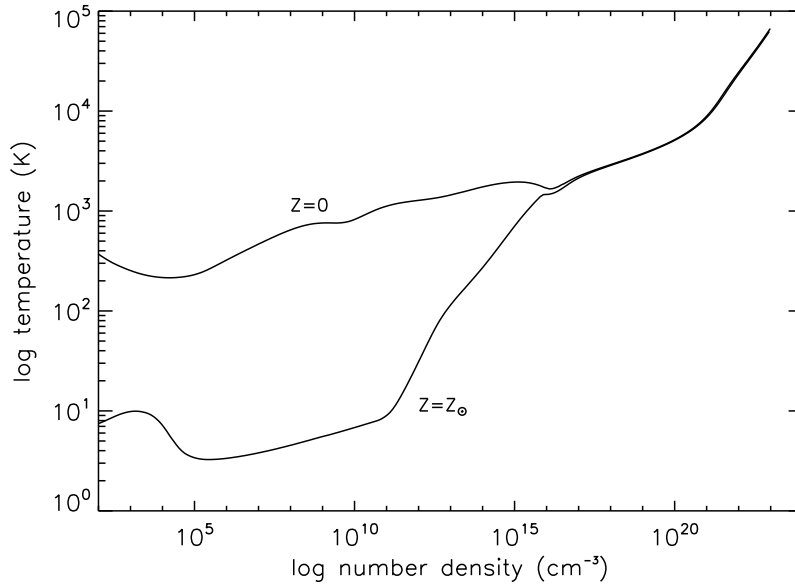


FIGURE 2. Temperature-density evolution for present day ($Z = Z_{\odot}$) and primordial ($Z = 0$) metallicities, based on the detailed thermal balance calculations of Omukai et al. [6]

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